



Composite Materials for Gas Turbine Engines Challenges and Opportunities

Dr. Ajay Misra
NASA Glenn Research Center
Cleveland, OH

Presented at Fourth International Conference on Recent Advances in Composite Materials, Goa, India, February 18-21, 2013



Outline

- Polymer matrix composites (PMCs)
- Ceramic matrix composites (CMCs)
- Multiscale Modeling

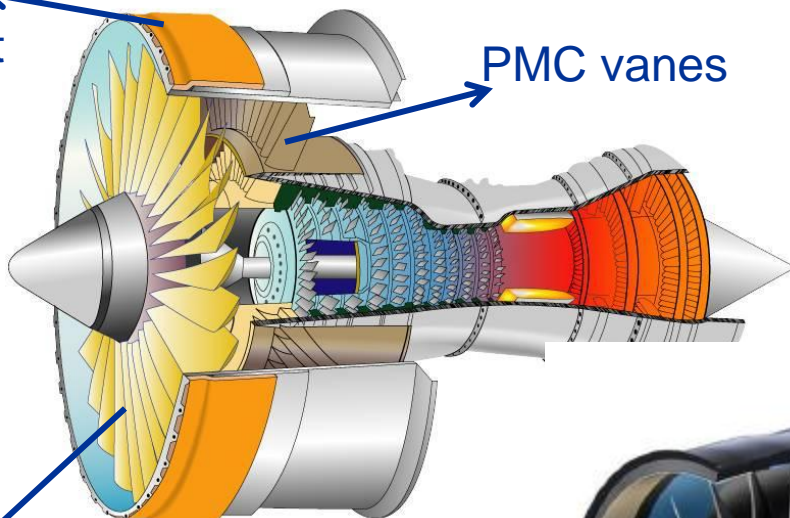
Will highlight on-going NASA work to address many challenges

Use of Polymer Matrix Composites (PMCs) in Gas Turbine Engines

PMC fan
containment
system

PMC vanes

PMC fan blades



Williams FJ44-4
(Cessna CJ4)

- ~25 inch fan diameter
- ~3,600 lbf thrust
- Titanium blade
- Hardwall case design
- Patent (NASA co-inventor)



GE Aviation Genx
(Boeing 747-8, Boeing 787)

- ~110 inch fan diameter
- 53,000 – 75,000 lbf thrust
- Composite blade
- Hardwall case design
- Patent (2 NASA co-inventors)

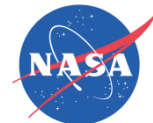
Benefits of PMC Fan Containment System:

- Weight reduction is ~25-30% (~ 350 lbs for a large engine)
- Typical 2X or greater factor for total weight



Challenges for use of PMCs in Gas Turbine Engines

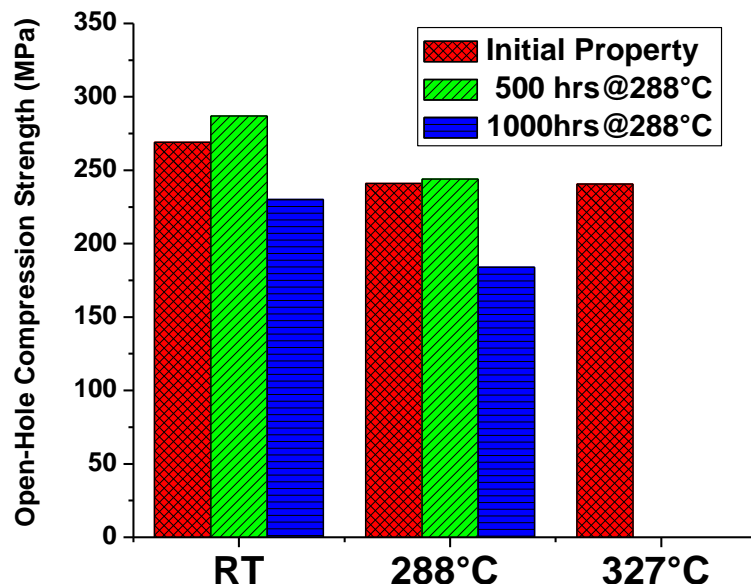
- Low to moderate temperature (-54° to 150°C)
 - Current use limited to fan blade and fan containment system
 - Need PMCs with higher temperature capability to extend the application range
- Analysis methods of damage mechanisms and structural failure modes not well established compared to metallic alternatives, particularly for blade impacts on fan containment system and transient loads due to direct impact of bird strike
 - Resulting in safety factor, decreasing weight savings benefits
 - Extensive time consumed in engine testing
- Test methodology to validate models and determine basic properties to be used in models
- Long-term durability (years) and effect of long-term exposure on key mechanical properties
- Innovative concepts to further reduce weight



High Temperature PMC Development

- ◆ Conventional PMR-15, PMR-II-50, AFR-PE4 polyimide composites all require solvent-based prepregs for part fabrication ⇒ *time consuming, costly and the use of solvents and diamines are hazardous*
- ◆ Fabricate net-shape polymer matrix composites from resins in the melt via RTM using preforms ⇒ *eliminate costly hand lay-up and hazard*
⇒ *produce 30% cost saving & 20% weight saving for complex parts*
⇒ *adaptable to automatic process*

Challenge: RTM requires low-melt viscosity that conventional polyimides cannot meet

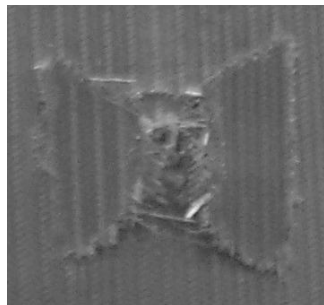
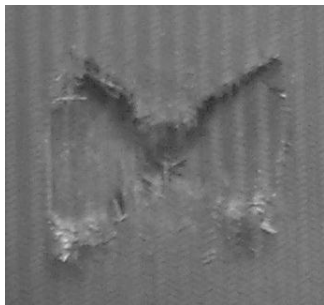


New, environmental friendly, RTM processable high temperature polyimide, RTM370, developed for 300°C application

Examples of impact failure modes

Range of material behavior observed

- Well defined initiation
- Crack growth along fiber directions

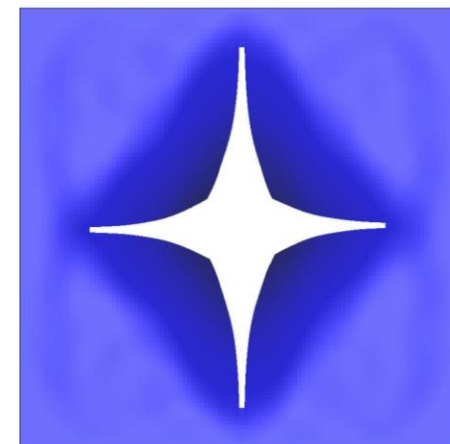


- Diffuse initiation
- Local intralaminar damage
- Damage remote from contact



- Extensive interlaminar delamination

Current analysis methods cannot account for architecturally dependent damage

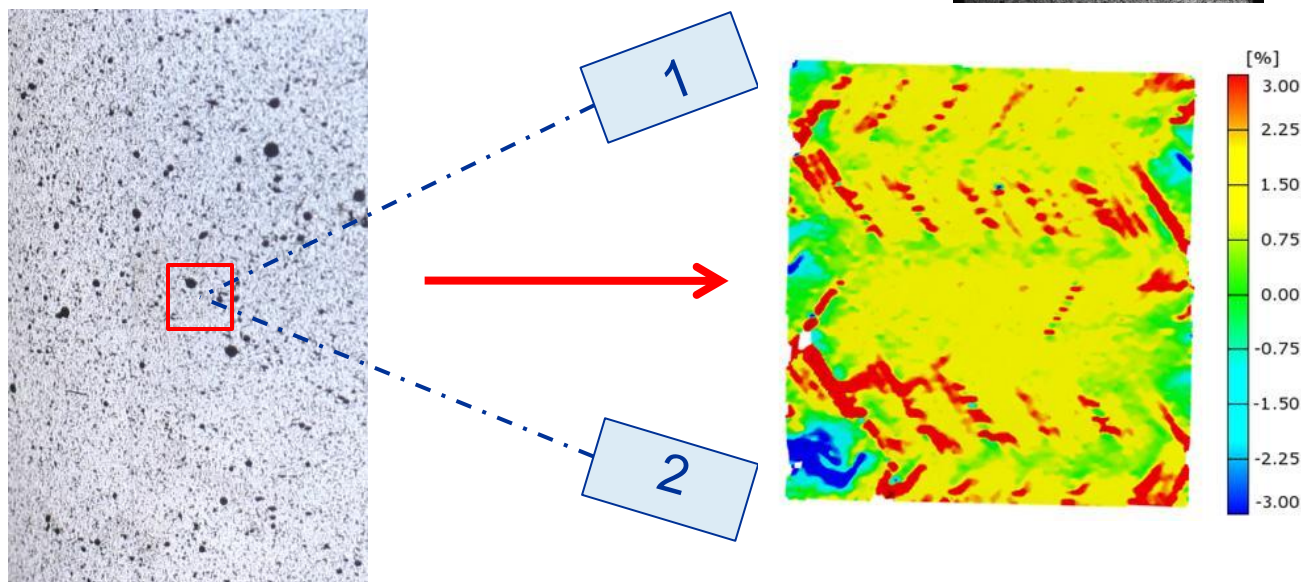
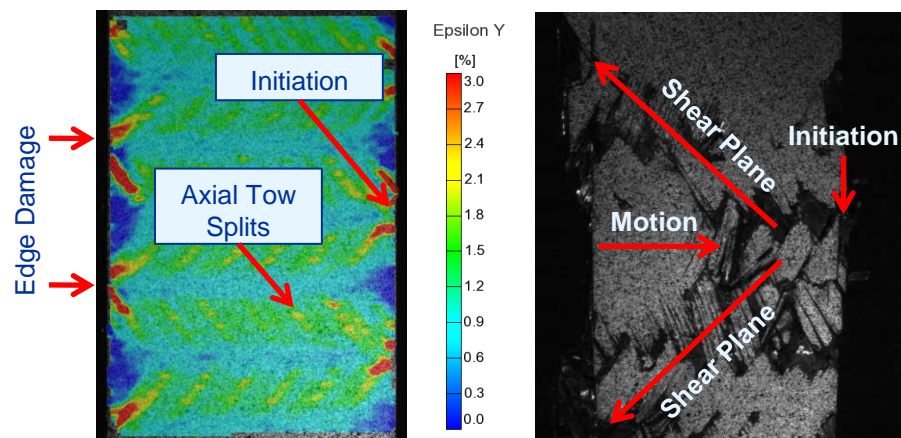


Impact simulation assuming homogeneous properties

Test Methodology to Identify Damage Mechanisms

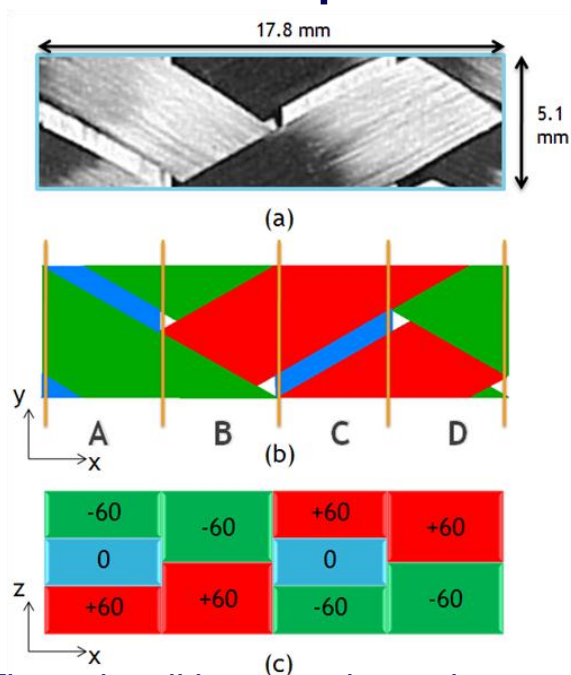
- Not a homogeneous material
- May have a relatively large architecture
- Local variations in architecture due to manufacturing and textile-to-mold conformance
- Coupon failure is often dependent on geometry
- Consensus on test coupon orientation not yet reached

Transverse Tension Edge Damage and Shear Failure

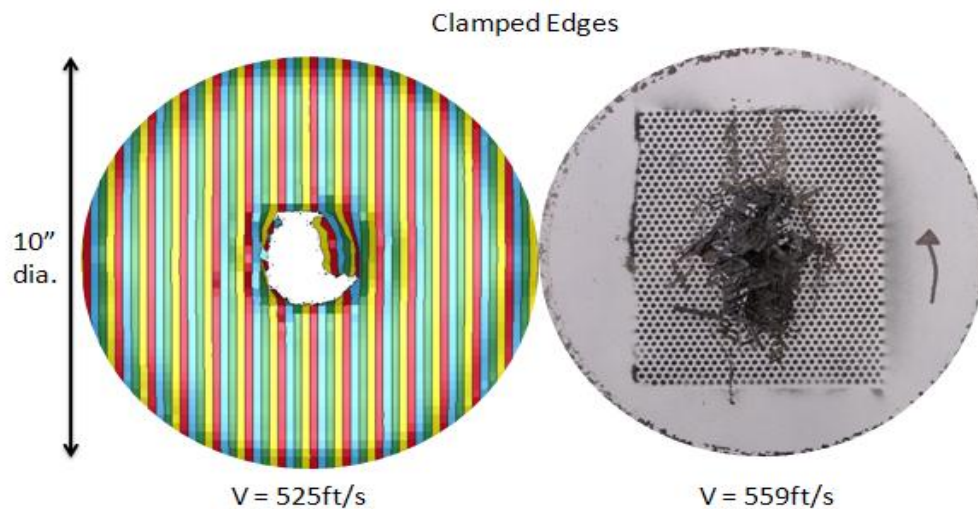


- Digital Image Correlation (DIC) provides the ability to evaluate strain field and deformation variability
- Identify damage mechanisms and failure initiation

Micromechanical Method for Modeling Impact Response of Triaxially-Braided PMCs



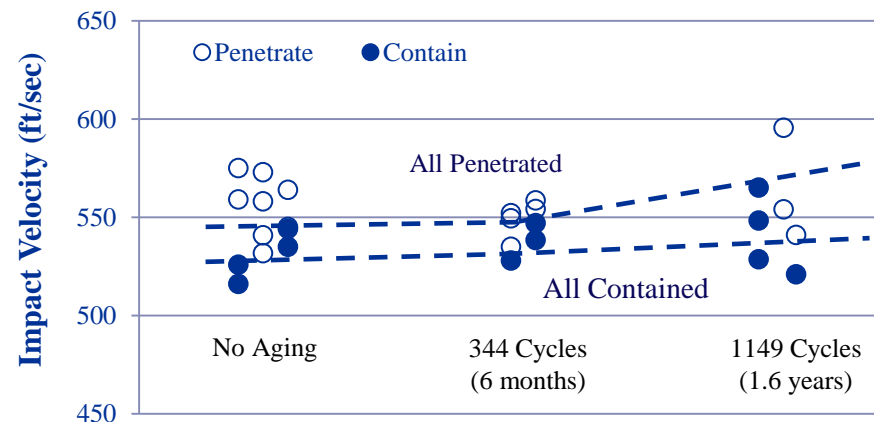
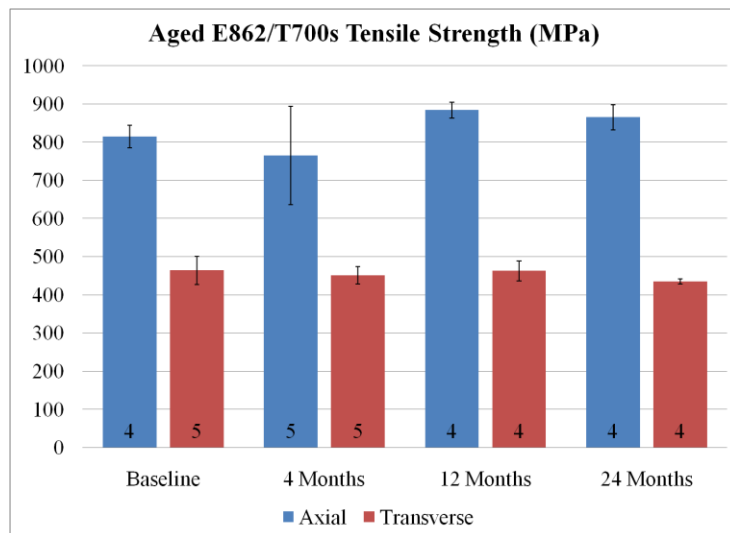
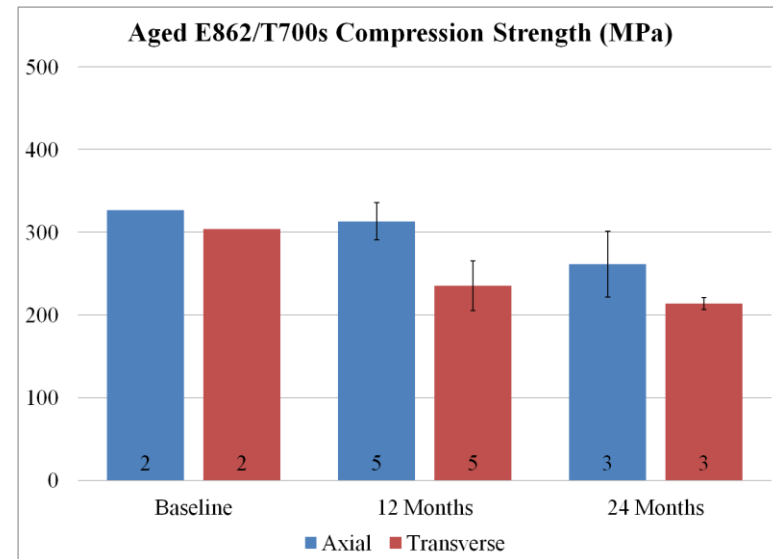
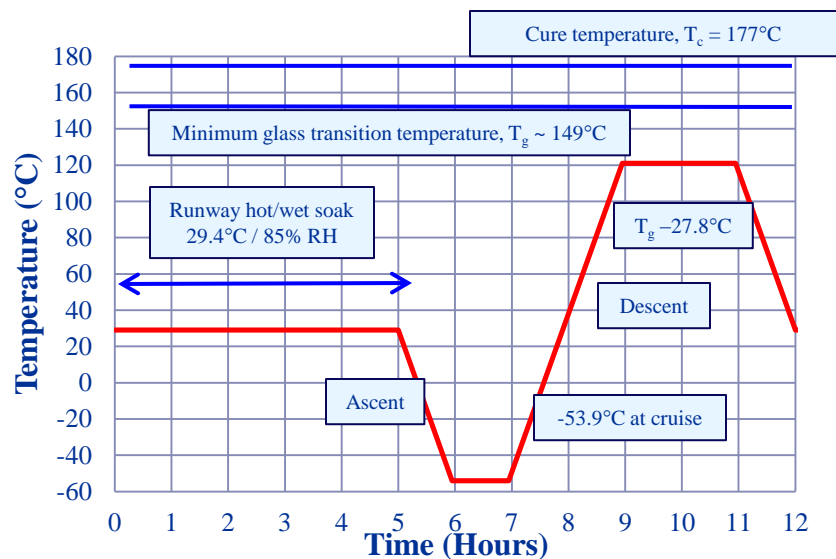
- The unit cell is approximated as a series of parallel laminated composites.
- Subcells are modeled as a continuum shell element.
- Equivalent stiffness and strength properties determined for each subcell.
- Variation in local fiber volume ratio between subcells is accounted for.
- Property data from experiments using full field strain measurements



- Penetration velocity well simulated.
- Impact damage patterns follow details of fiber architecture.
- Impact damage patterns in simulation more rounded than experiments.
- Discrepancies may be due to strain rate effects.



Aging Using a Hygrothermal Cycling



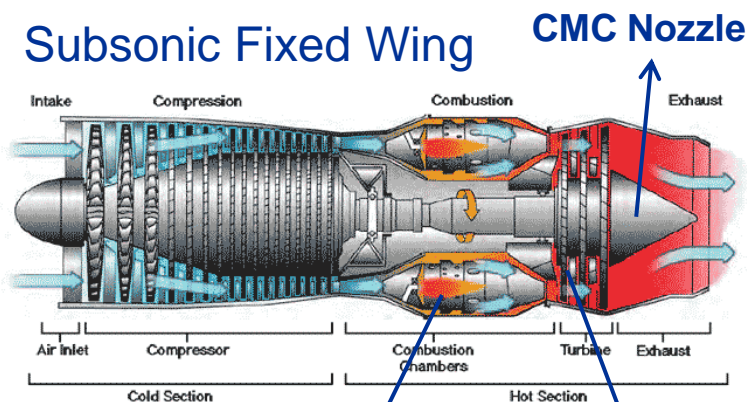
Innovative Weight Reduction Concepts for Fan Containment System



Fiber reinforced foam core sandwich structure offers significant weight reduction opportunities and potential for multifunctional (e.g., impact resistance plus noise reduction) fan containment structures

Ceramic Matrix Composites (CMCs) for Gas Turbine Engines

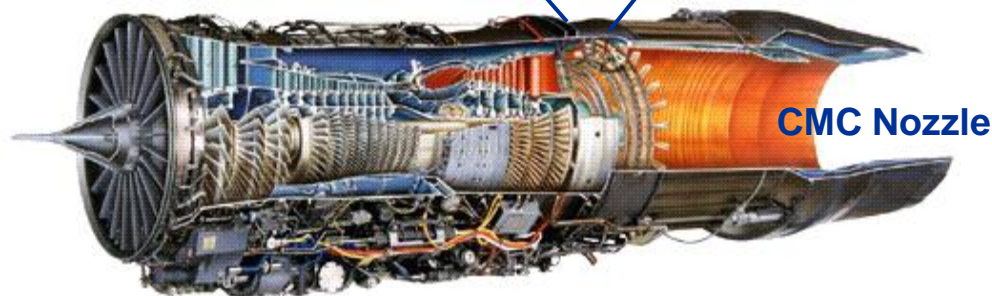
Subsonic Fixed Wing



CMC
Combustor
Liner

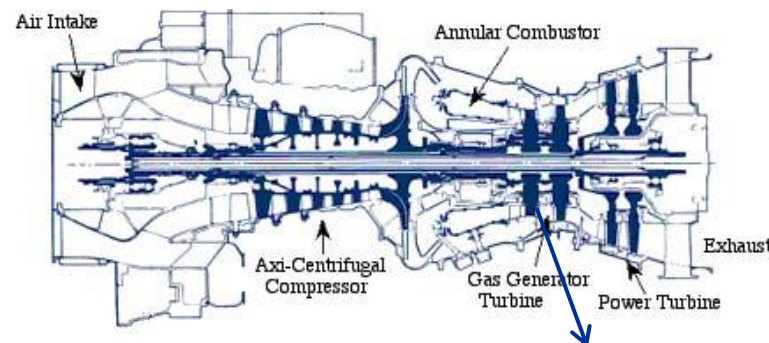


CMC Vane
and Blade



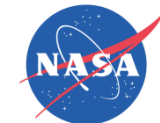
Supersonic

Subsonic Rotary Wing

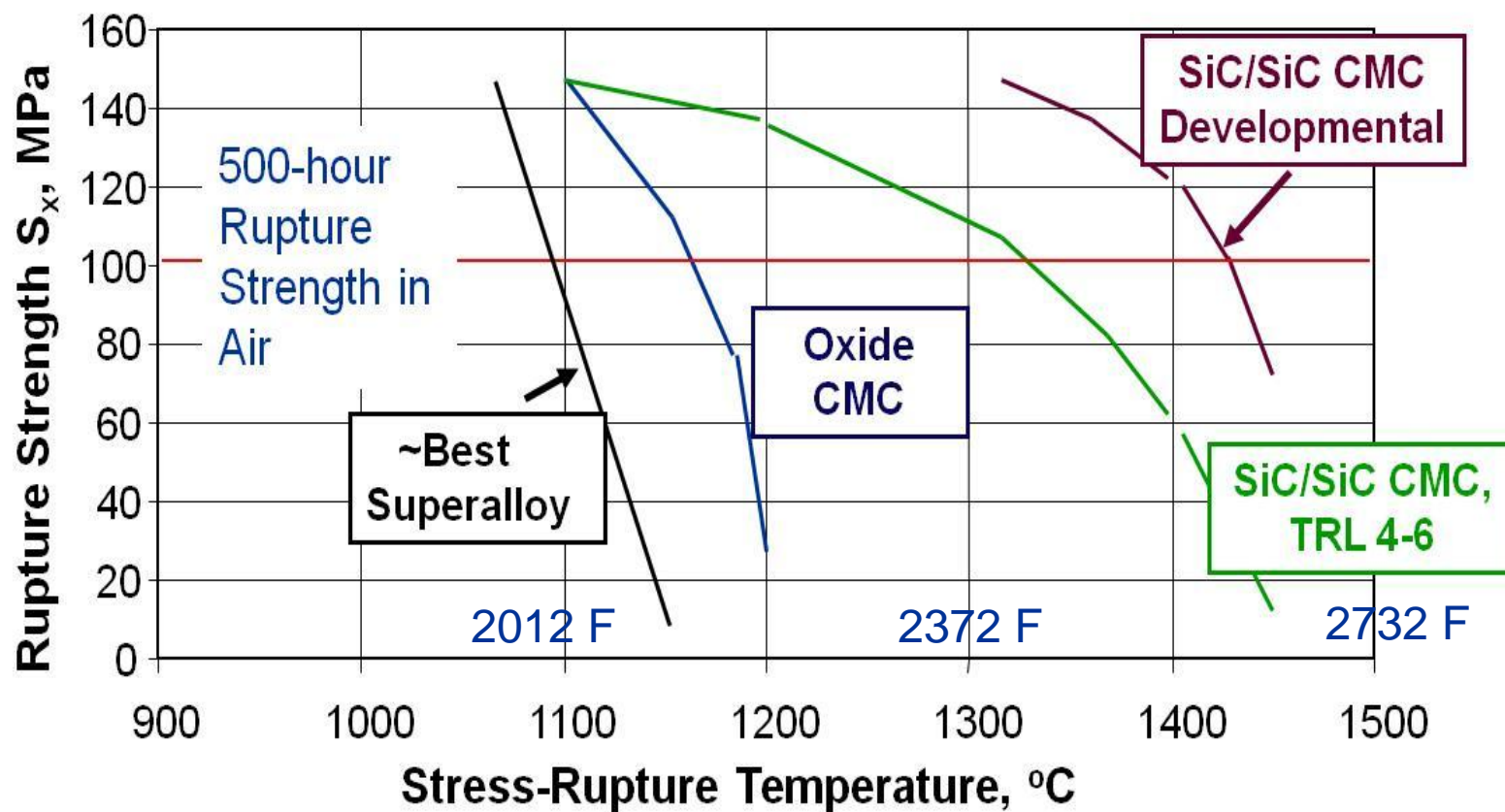


Benefits:

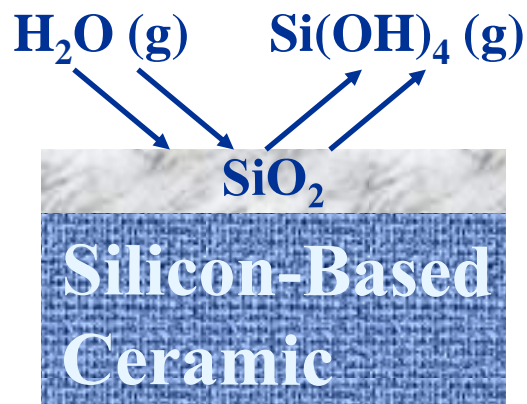
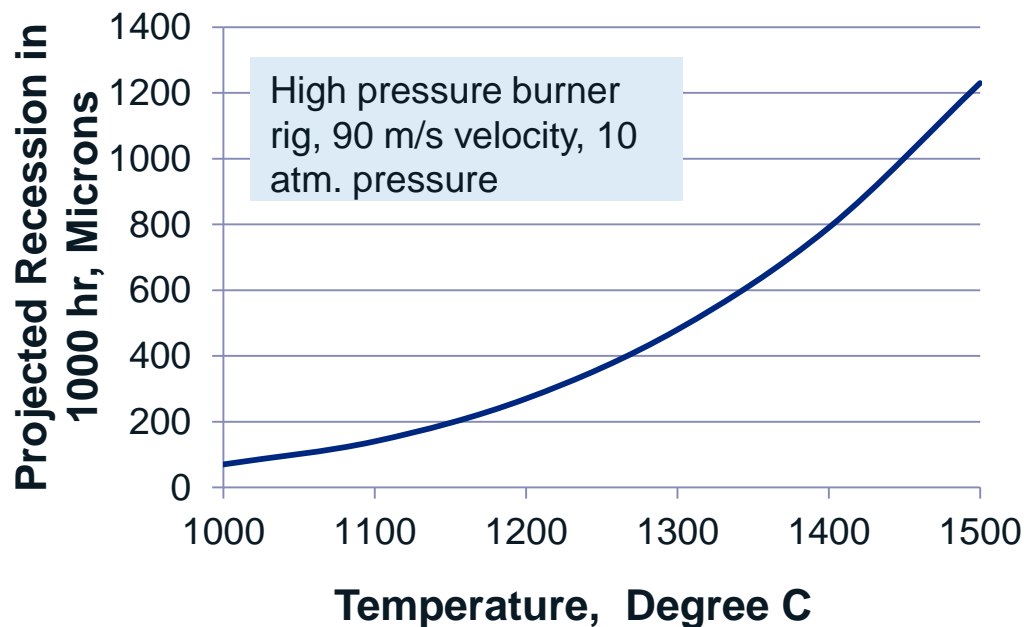
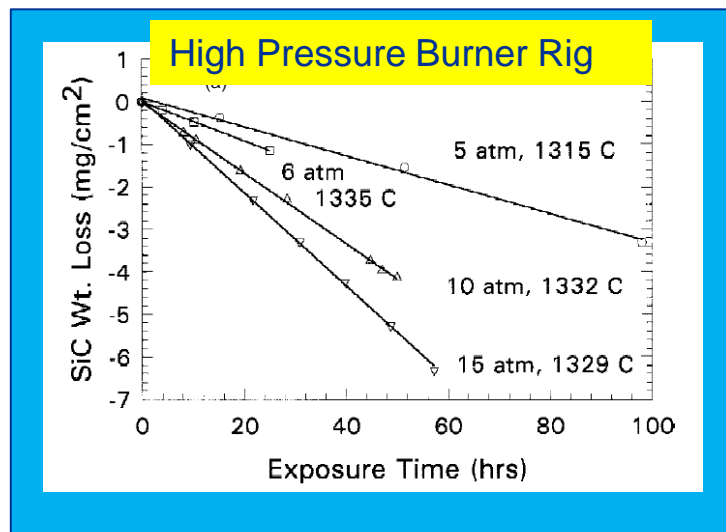
- Higher temperature capability enabling high OPR
- Lightweight, particularly for LPT vanes
- Less cooling, increasing efficiency



SiC/SiC CMC – Preferred CMC for Gas Turbine Engine Hot Section Components

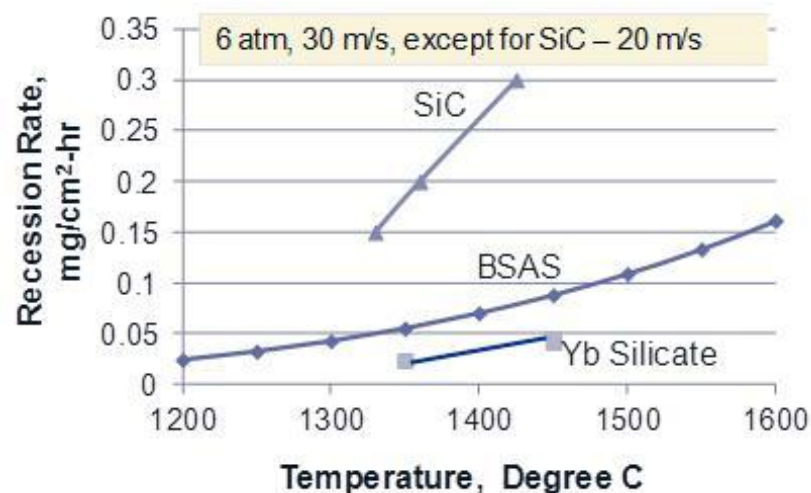
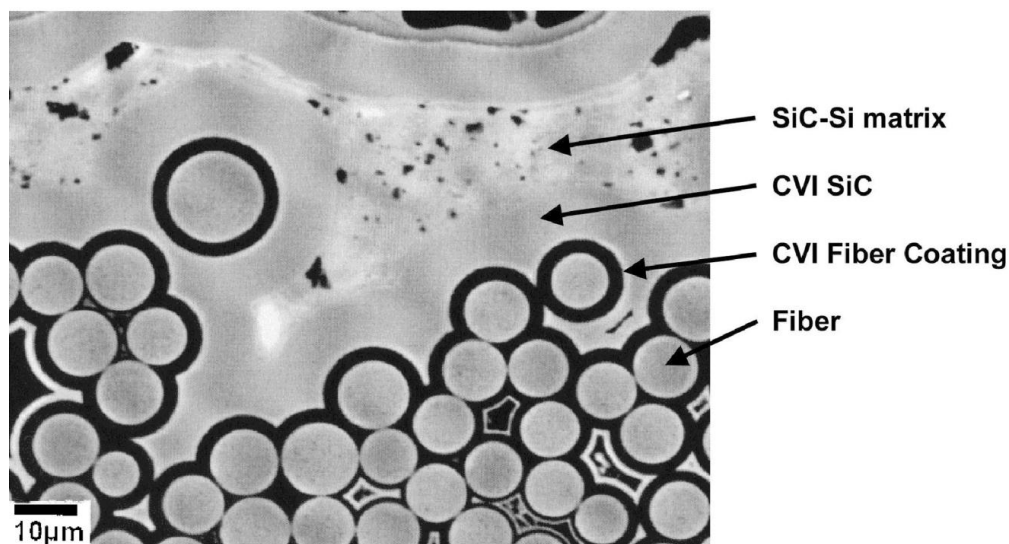
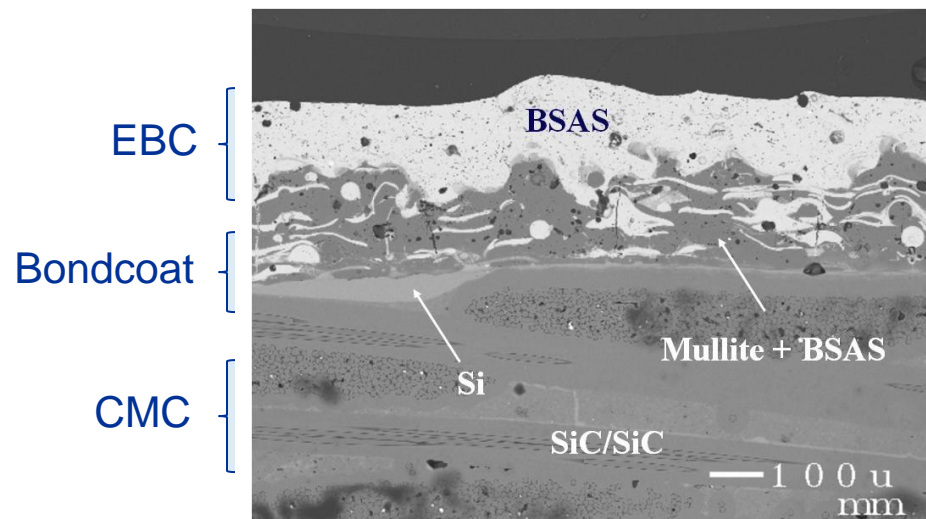


Surface Recession of SiC/SiC CMC



State-of-the-Art SiC/SiC CMC System

- State-of-the-art SiC/SiC CMC limited to 1315°C (2400°F) temperature capability due to
 - Presence of Si in matrix and bondcoat
 - Degradation in fiber creep strength
 - Reaction between different layers of EBC and decomposition of EBC

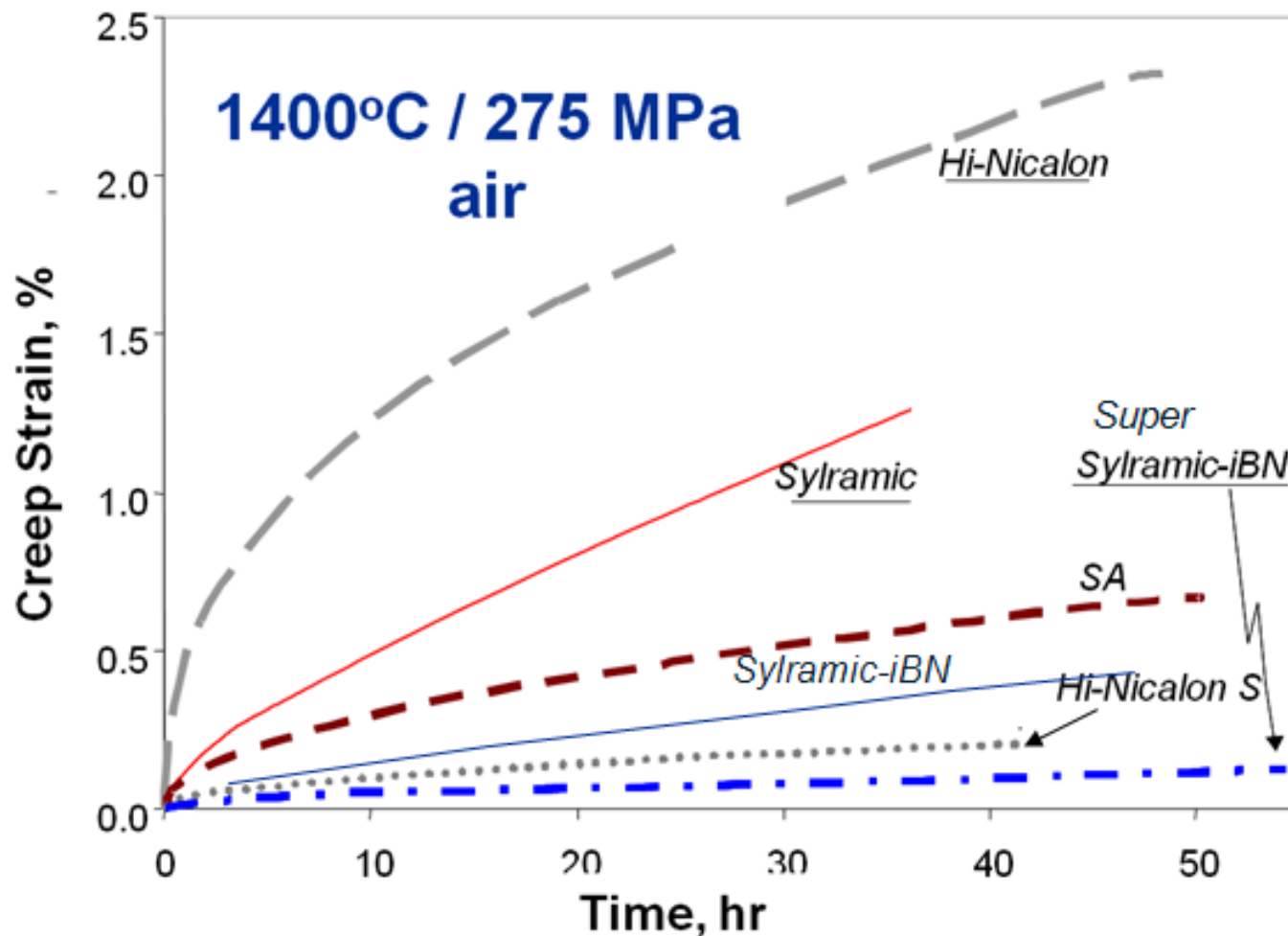




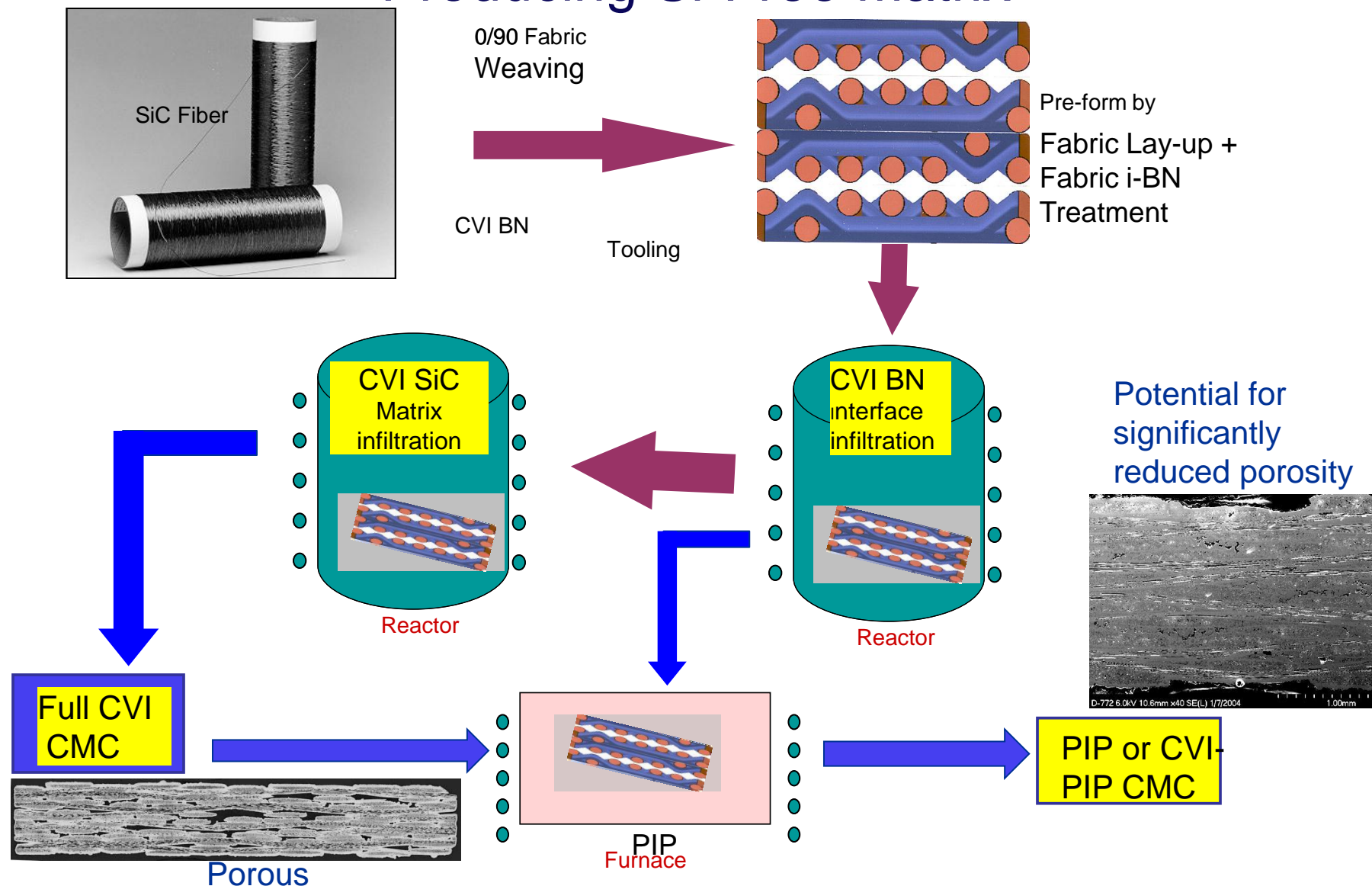
Approaches for Increasing Temperature Capability of SiC/SiC CMC

- New SiC fiber with increased creep rupture strength
- Si-free dense matrix
- Recession-resistant EBC at higher temperatures
- Combined EBC/thermal barrier coating to lower EBC and CMC temperature
- Engineered, multilayer EBC to address the issue of Si bondcoat and thermomechanical degradation

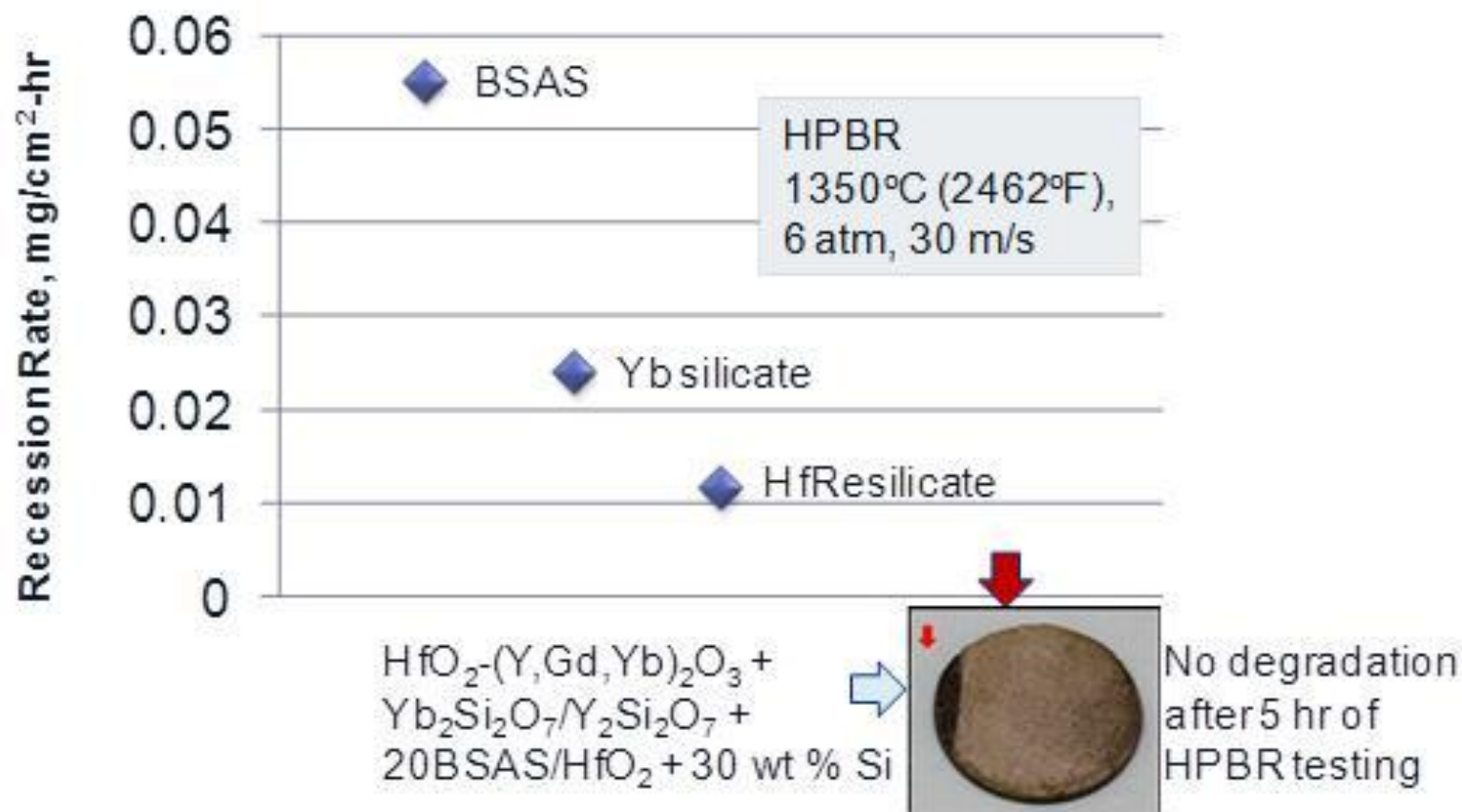
Development of Advanced SiC Fiber



Multiple Processing Approaches for Producing Si-Free Matrix

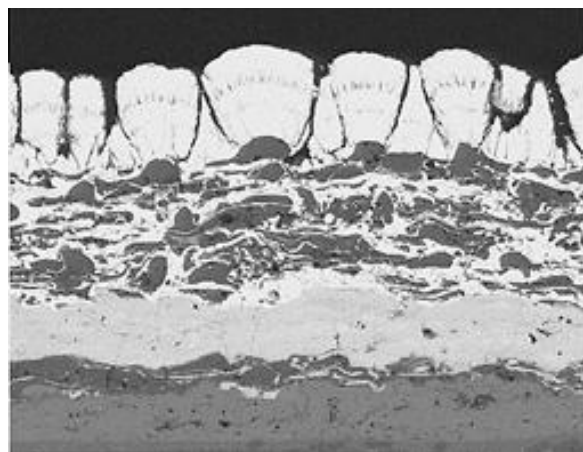


Complex Silicate Environmental Barrier Coatings Show Promise



- Long-term durability needs to be demonstrated
- Need new ceramic coating chemistries for environmental stability at temperatures greater than 1482°C (2700°F)

Development of Combined Environmental Barrier/Thermal Barrier Coating System



TBC

Interlayer ($\text{ZrO}_2 + \text{BSAS}$)

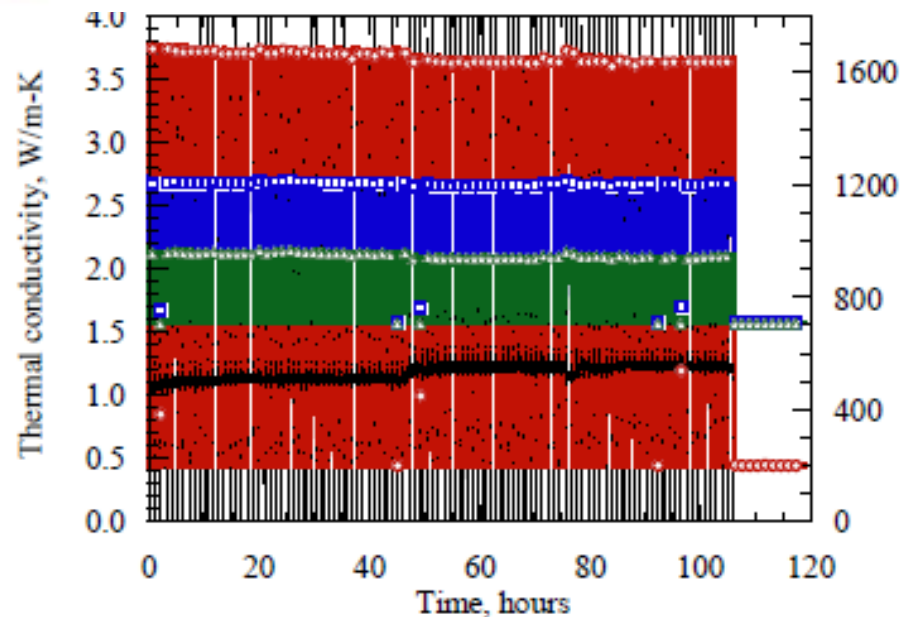
EBC (BSAS)
Si Bondcoat

No degradation after
100, 1-hr cycle in laser
heat flux test at
 1704°C (3100°F)

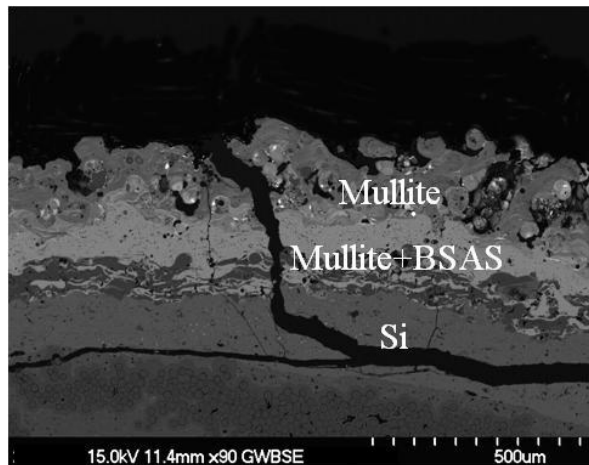


—○— T_{surface}
—□— $T_{\text{interface}}$
—○— T_{back}

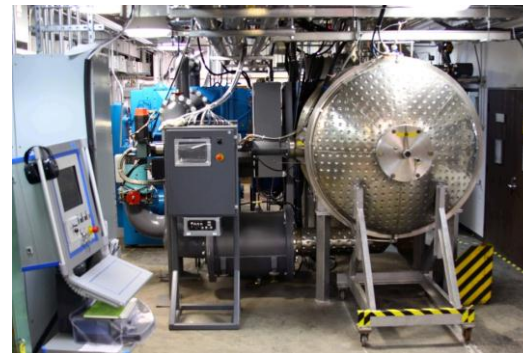
- Combined EBC/TBC can provide temperature capability greater than 1650°C (3000°F); however, coatings are thick and would be suitable for static components.
- Need long-term durability demonstration



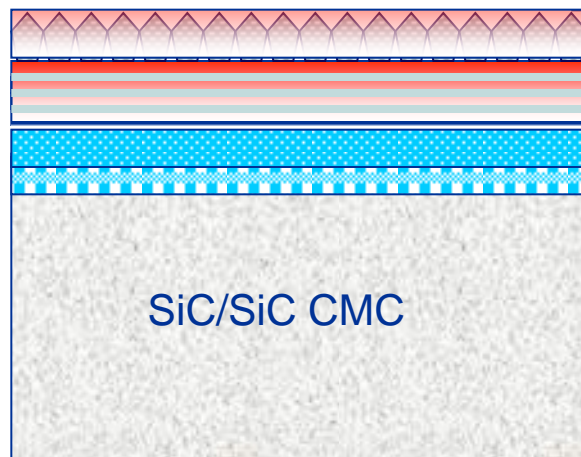
Engineered, Multi-Layer EBC for Long-Term Durability



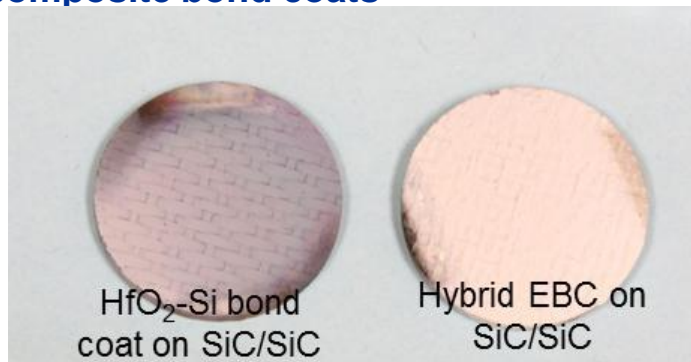
Cracking and delamination of coating under high heat flux conditions



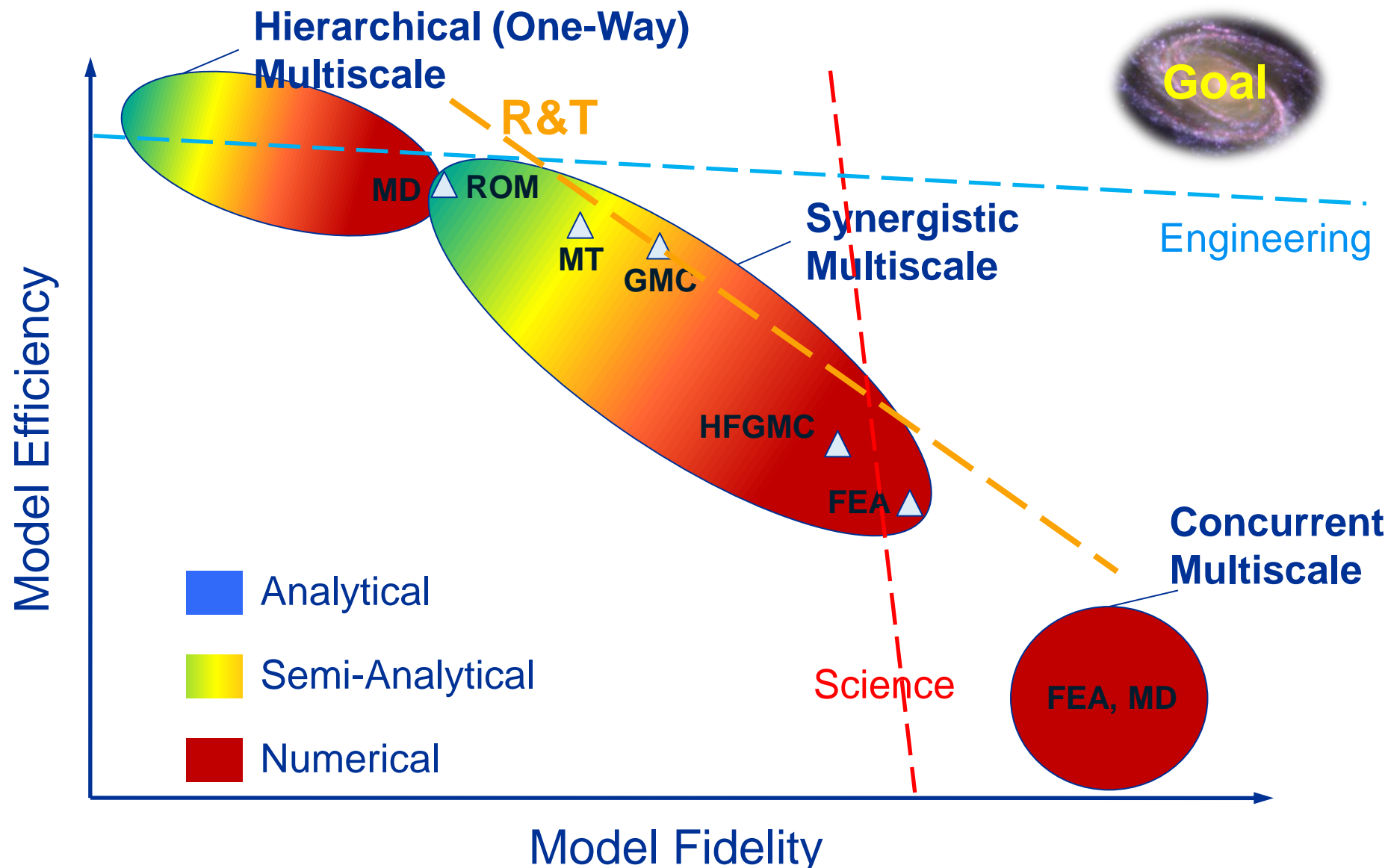
Plasma Spray – Physical Vapor Deposition (PS-PVD) process for thin, multilayer coatings



Low expansion REHfO_2 -Aluminosilicate
Interlayer: Compositional layer graded system
RE doped mullite- HfO_2 , or rare earth silicate EBCs
Ceramic composite bond coats

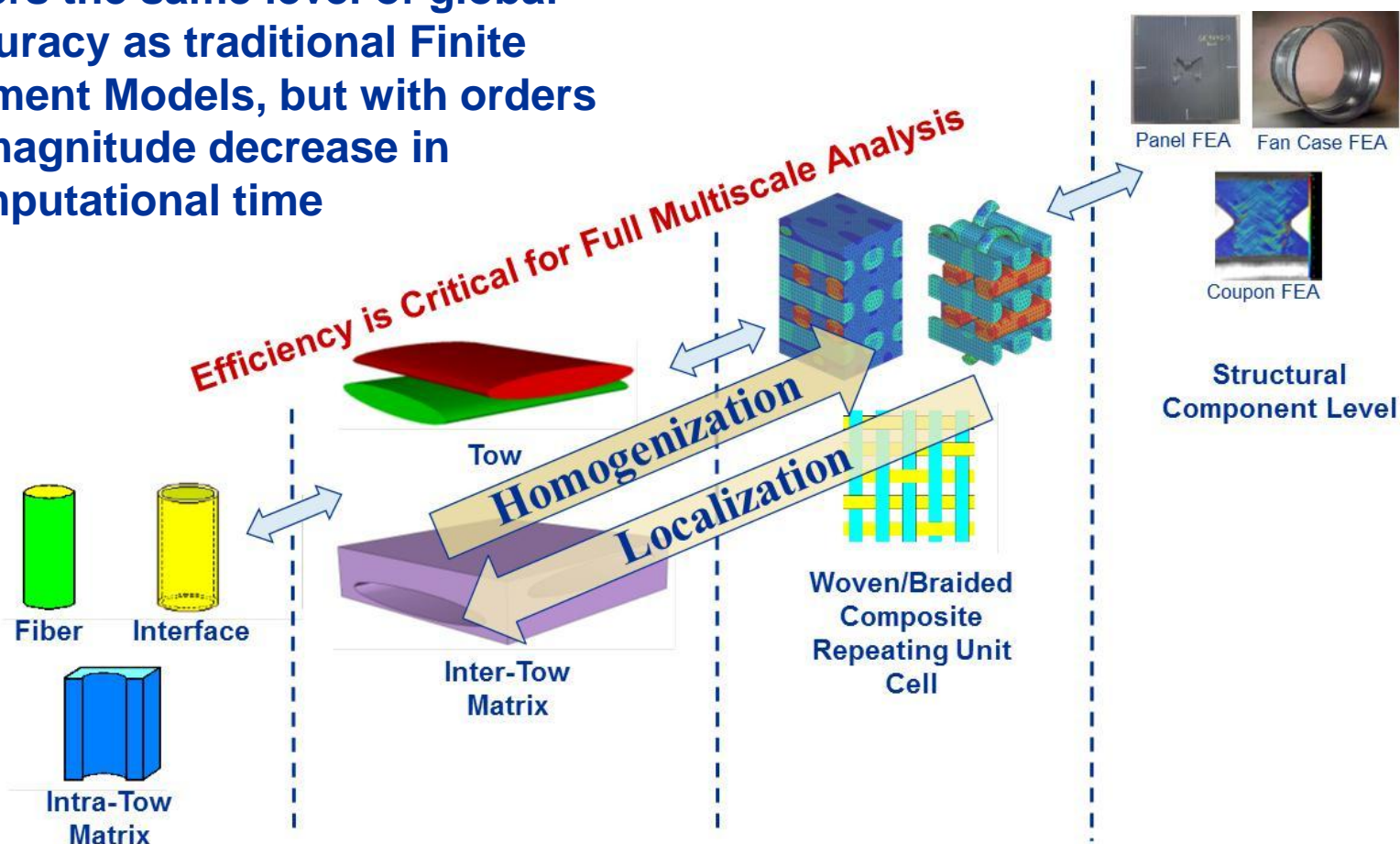


Goal is to Balance Efficiency vs Fidelity



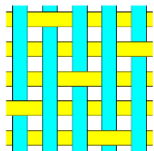
Integrated multiscale Micromechanics Analysis Code (ImMAC) Based on Generalized Method of Cells

Offers the same level of global accuracy as traditional Finite Element Models, but with orders of magnitude decrease in computational time

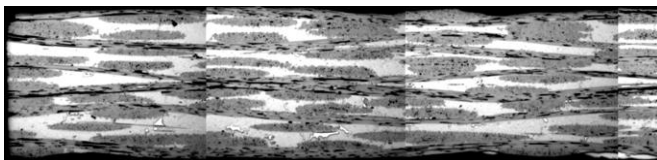


Prediction of Creep of a Woven CMC Using ImMAC

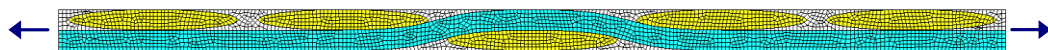
5 harness satin
weave pattern



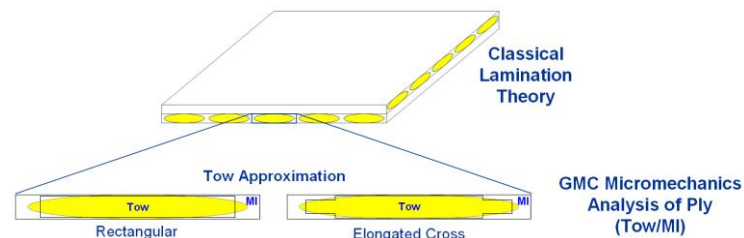
Optical Micrograph of 5 harness satin SiC/SiC



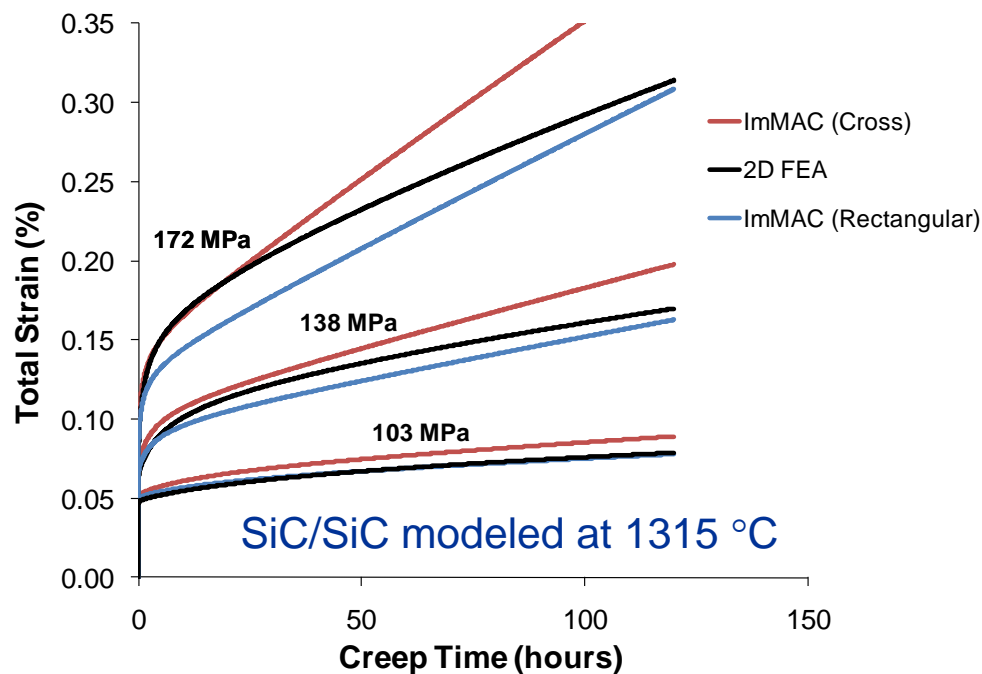
2D Finite Element Model ~2 hours



ImMAC Multiscale Lamination Theory ~1 second



ImMAC Multiscale Lam. Theory vs. 2D FEA



- Multiscale lamination theory ignores undulation but captures 3D unit cell geometry
- 2D FEA captures undulation, but geometry is unrealistic in the 3rd dimension
- Both models give similar results - within experimental scatter
- ImMAC is ~7000 times more efficient
- ImMAC practical for backing out material properties and trade studies



Concluding Remarks

- Will see increase in use of composite materials for gas turbine engines
 - Higher temperature PMCs extending the range of application of PMCs
 - Integrated PMC structures
 - Hybrid PMC structures
 - CMC combustor liner, shroud, low pressure turbine blades and vanes, high pressure turbine vanes
- Significant challenges remain for achieving long-term durability of CMCs beyond 1315°C (2400°F)
 - Advanced fibers
 - Dense, Si-free matrix
 - Environmental barrier coatings
- Validated multiscale models incorporating damage mechanisms needed for composites